Southern Hemisphere climate response to ozone changes and greenhouse gas increases

Drew T. Shindell and Gavin A. Schmidt
NASA Goddard Institute for Space Studies, New York, New York, USA

Received 10 June 2004; revised 17 August 2004; accepted 24 August 2004; published 25 September 2004.

[1] While most of the Earth warmed rapidly during recent decades, surface temperatures decreased significantly over most of Antarctica. This cooling is consistent with circulation changes associated with a shift in the Southern Annular Mode (SAM). It has been suggested that both Antarctic ozone depletion and increasing greenhouses gases have contributed to these trends. We show that a climate model including the stratosphere and both composition changes reproduces the vertical structure and seasonality of observed trends. We find that the two factors have had comparable surface impacts over recent decades, though ozone dominates above the middle troposphere. Projected impacts of the two factors on circulation over the next fifty years oppose one another, resulting in minimal trends. In contrast, their effects on surface climate reinforce one another, causing a departure from the SAM pattern and a turnabout in Antarctic temperatures, which rise more rapidly than elsewhere in the Southern Hemisphere. *INDEX TERMS:* 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 1620 Global Change: Climate dynamics (3309); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 9310 Information Related to Geographic Region: Antarctica. **Citation:** Shindell, D. T., and G. A. Schmidt (2004), Southern Hemisphere climate response to ozone changes and greenhouse gas increases, *Geophys. Res. Lett.*, *31*, L18209, doi:10.1029/2004GL020724.

1. Introduction

[2] Many aspects of Southern Hemisphere (SH) extra-tropical climate change have been well documented during recent decades. These include warming over mid-latitudes and the Antarctic peninsula and cooling over most of the rest of that continent, an increase in the speed of the westerlies over the Southern Ocean, and a shift in mass from high to middle latitudes seen in sea level pressure (SLP) and in consistent changes in geopotential heights and winds extending up into the stratosphere [*Thompson et al.*, 2000; *Marshall*, 2002; *Schneider and Steig*, 2002; *Thompson and Solomon*, 2002; *Jones and Widmann*, 2003; *Marshall*, 2003]. The leading variability pattern in the Southern extratropics in all of these meteorological fields is the SAM (or Antarctic Oscillation, hereafter referred to as the SAM) [*Gong and Wang*, 1999; *Thompson et al.*, 2000; *Schneider and Steig*, 2002; *Jones and Widmann*, 2003]. Several indicies representing the mean state of this equivalent barotropic mode have been defined (see below) and have exhibited a positive trend over the past two to three decades (i.e., the oscillation has favored the 'high' phase, while the pattern itself has remained stable). The observed climate changes generally project very closely onto this pattern, indicating that the SAM shift is largely responsible for the divergent behavior of Antarctic surface temperatures from those elsewhere. For example, approximately 90% of the cooling at South Pole and eastern Antarctic stations is correlated with the SAM index trend [*Thompson and Solomon*, 2002]. A similar fraction of the trend in high latitude geopotential heights is associated with the SAM index trend, though the warming over the Antarctic peninsula shows a weaker correlation and may have also resulted from local phenomenon [*Marshall*, 2002]. Shifts in a SAM-like pattern were already apparent about a decade ago [*Hurrell and van Loon*, 1994; *Karoly et al.*, 1996], and have continued since, though internal climate variability makes the magnitude difficult to constrain with only two to four decades of data [*Marshall*, 2003].

[3] General circulation model (GCM) simulations have shown that imposing Antarctic ozone depletion leads to an enhancement of the SAM index [*Kindem and Christiansen*, 2001; *Sexton*, 2001; *Gillett and Thompson*, 2003]. Models forced by increasing greenhouse gases (well-mixed) also respond with a positive SAM index shift [*Fyfe et al.*, 1999; *Kushner et al.*, 2001; *Stone et al.*, 2001; *Cai et al.*, 2003; *Rauthe et al.*, 2004]. Here we compare the first simulations using both factors with observations, and project the climate response to estimated future trends.

2. Experimental Setup

[4] We use the Goddard Institute for Space Studies GCM model II' version run at 4 by 5 degree horizontal resolution with 23 vertical layers extending up into the mesosphere in the configuration used for atmospheric chemistry simulations [*Shindell et al.*, 2003]. The basic physics of the model are similar to those used in recent climate studies [*Hansen et al.*, 2002], however this version also includes a parameterization for gravity waves based upon convective activity, wind shear and orography to better represent stratospheric processes. The atmospheric model is coupled to a mixed-layer ocean with heat diffusion into the deep ocean and thermodynamic sea-ice. Three ensembles of three simulations each were performed, all beginning in 1945 and extending through 2055. All runs used initial conditions taken from different points in a stable control run. They were driven by increasing greenhouse gases ('GHG'), stratospheric ozone changes ('O3') and both these forcings ('GHG+O3'). Increasing greenhouse gases were based upon observations through 1999 and subsequently based

0094-8276/04/2004GL020724$05.00

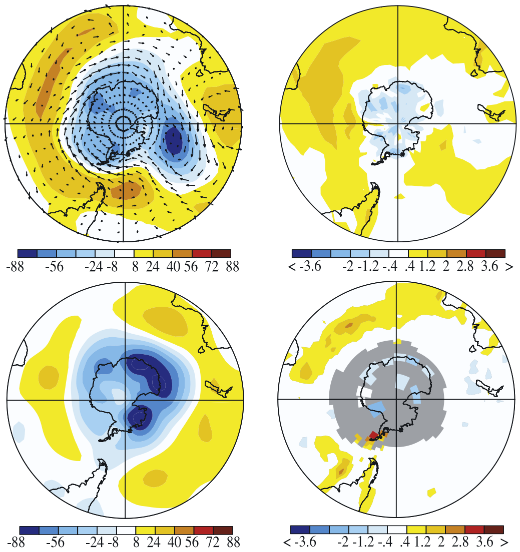

Figure 1. Observed and modeled Dec–May SH trends. 500 hPa geopotential height trends (m) are for 1979–2000 from the simulations forced by combined greenhouse gas and ozone changes (top left) and in observations (bottom left). Surface air temperature trends (C) are for 1969–2000 in the same model (top right), and in observations (bottom right) from meteorological stations [*Hansen et al.*, 2001] and SST reconstructions [*Hansen et al.*, 2001; *Rayner et al.*, 2003] (though Southern Ocean data is relatively sparse and subject to inhomogeneities due to changing data sources). Modeled trends in 925 hPa near-surface winds (m/s) from 1979–2000 are also shown (top left), with the time period chosen for comparison with previously published observations [*Thompson and Solomon*, 2002; *Gillett and Thompson*, 2003]. Color scales are consistent with Figure 4. The maximum wind vector is 3.5 m/s. Grey indicates no data. Antarctic station data are expanded for visibility.

upon projections following IPCC scenario B2, a mid-range estimate of future emissions. Transient stratospheric ozone changes were prescribed according to earlier chemistry-climate simulations [*Shindell et al.*, 1998]. Those experiments simulated past Antarctic ozone trends in good agreement with observations and similar to those projected in other chemistry-climate models [*Austin et al.*, 2003].

3. Results

[5] The GHG+O3 ensemble simulations reproduce the observed trends over the past two to three decades in 500 hPa geopotential heights, surface air temperature, and surface winds quite well (Figure 1). The heights show a fairly zonal pattern of decreases over the polar cap and increases at middle latitudes. Modeled average high-latitude decreases are slightly weaker than in observations, but well within their uncertainty (Table 1). Consistent with the height trends, there is an increase in the near-surface zonal westerlies at ~65°S, and a largely zonally symmetric response in surface temperatures with cooling over most of Antarctica and warming at lower latitudes including the Antarctic peninsula and the southern tip of South America.

[6] The positive SAM index shift seen in the GHG+O3 simulations is robust among ensemble members (Figure 2a),

Table 1. SAM Index Trends[a]

500 hPa Heights (m/yr)	1970–1999	2000–2050	
Observations	−1.54 ± 0.96		
Ozone depletion (O3)	−1.26 ± 0.54	0.51 ± 0.22	
Greenhouse gases (GHG)	−0.38 ± 0.29	−0.51 ± 0.14	
O3+GHG	−1.19 ± 0.33	−0.13 ± 0.16	
Sea Level Pressure (hPa; 1958–2000)	**40°S**	**65°S**	**40°S–65°S**
Observations	0.9	−1.7	2.7 ± 2.7
Ozone depletion (O3)	0.0	−1.1	1.1 ± 1.4
Greenhouse gases (GHG)	0.4	−1.3	1.7 ± 0.9
O3+GHG	0.3	−1.6	1.9 ± 1.2

[a]Height trends are December–May averages poleward of 65°S in the model and calculated from radiosonde data [*Thompson and Solomon*, 2002], while SLP trends are annual averages based on station data from locations near the indicated latitudes [*Marshall*, 2003] and using zonal averages in the model. Uncertainties are the 95% confidence interval (observed SLP trends are significant at the 90% level). Modeled results are averages over three member ensembles. Single simulations have comparable variability to the observations.

as are the ensemble responses to the individual forcings as evidenced by their comparable uncertainty ranges (Table 1). Examination of the GHG and O3 simulations shows the impact of the individual forcings. A positive shift results from increasing greenhouse gases, while ozone depletion and recovery induce positive and negative SAM responses, respectively (Figures 2a and 2b). The relative importance of these factors depends upon the choice of index, however. Using the December–May area-weighted average 500 hPa geopotential height poleward of 65°S [*Thompson and Solomon*, 2002], ozone depletion dominates the overall recent trends (Table 1 and Figure 2b). Using annual average SLP trends near 40°S and 65°S [*Gong and Wang*, 1999; *Marshall*, 2003], the impact of increasing greenhouse gases seems to be at least as important, however (Table 1). Similar behavior is seen at 500 hPa, so that a SAM index based on

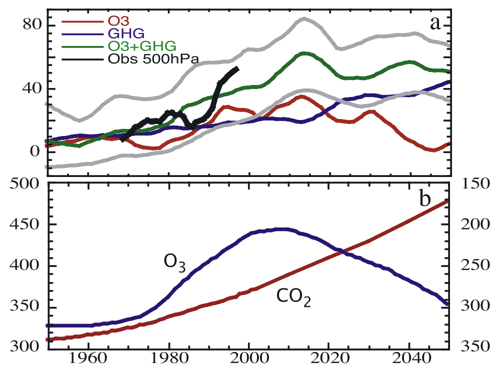

Figure 2. Time evolution of the 500 hPa SAM index (m) in the indicated model runs and in observations from radiosondes [*Thompson and Solomon*, 2002] (a), and of greenhouse gas and ozone forcing trends input to the GCM (b). The SAM index is the Dec–May area weighted average height poleward of 65°S (inverted, zero is arbitrary). Grey lines show the range of the GHG+O3 ensemble. For greenhouse gas trends, CO_2 values are shown, though trends in all the well-mixed greenhouse gases were included. For ozone, October average total column poleward of 70°S is shown. SAM index and ozone values are smoothed with a ten-year filter.

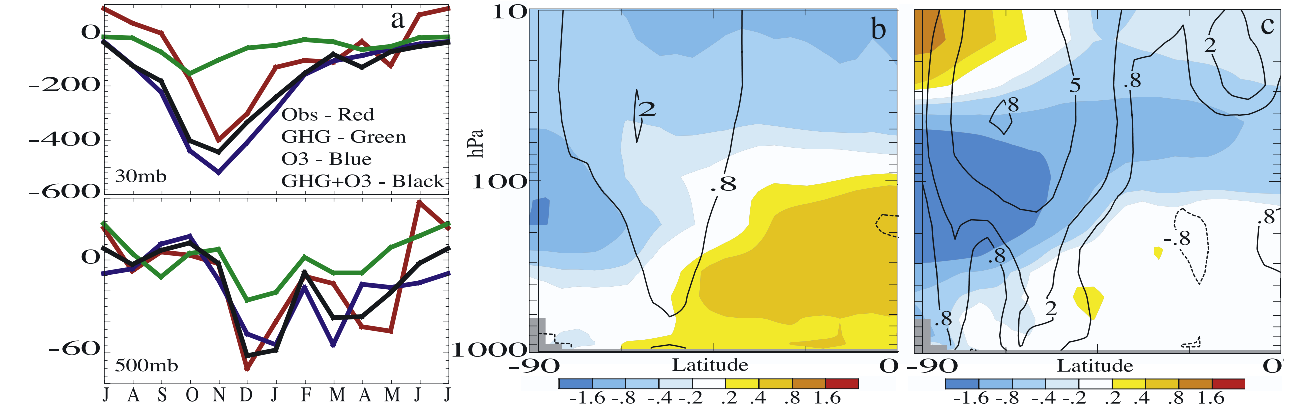

Figure 3. Seasonal 1969 to 1998 trends in 60–90°S geopotential height (a) at 30 hPa (top), and 500 hPa (bottom) in observations [*Thompson and Solomon*, 2002] and GCM simulations. Zonal mean Dec–May temperature (C, colors) and zonal wind (m/s, contours) linear trends from 1970 to 1999 in the simulations forced by increasing greenhouse gases (b) and by ozone depletion (c).

the height difference between middle and high latitudes at that level shows comparable impacts from the two forcings. This is consistent with the global effect of greenhouse gases compared with the more localized influence of Antarctic ozone depletion. In the lower stratosphere, the influence of ozone loss is clearly paramount, leading, for example, to a zonal wind anomaly roughly 3 times greater than that caused by greenhouse gases during the past three decades (Figures 3b and 3c). Overall, the influence of ozone becomes more important for higher latitudes and altitudes, but the extratropics-wide SLP signals of greenhouse gases and ozone are not statistically different.

[7] Observations from ~65°S to 75°S indicate that the strongest height trends appear in November in the lower stratosphere, descending to the upper and middle troposphere during December [*Thompson and Solomon*, 2002]. The model is able to capture this seasonality and the time lag of the tropospheric response quite well, with ozone dominating the stratospheric trends (Figure 3a). The lower stratospheric seasonality is sensible as the radiative perturbation from ozone depletion maximizes there during late austral spring. The lagged response of the troposphere suggests that accurately representing the stratosphere may be important to properly model SH circulation trends.

[8] Surface observations show that the SLP-based SAM index trends appear to be of similar magnitude in all seasons except for September–November, though the statistics are poor [*Marshall*, 2003]. This suggests that ozone depletion, with a very strong seasonality, is not dominating the surface trends as much as those aloft. Indeed, previous simulations driven by ozone depletion alone showed a strong DJF response but could not reproduce observed MAM trends in the lower troposphere [*Gillett and Thompson*, 2003]. Conversely, previous simulations driven by greenhouse gases alone showed a weaker DJF response than the observations suggest [*Fyfe et al.*, 1999; *Kushner et al.*, 2001]. Observations thus suggest, and previous modeling allows, a sizeable role for both ozone and greenhouse gases in the lower atmosphere.

[9] We believe the modeled trends are initiated by the meridional temperature gradients induced by the changing ozone and greenhouse gas abundances, which alter wave propagation (not shown) and end up strengthening the westerly flow throughout the depth of the atmosphere (Figures 3b and 3c). Observational analyses indicate that the Antarctic vortex has strengthened over recent decades [*Waugh et al.*, 1999; *Zhou et al.*, 2000], and the observed enhancement of the westerlies extends all the way to the surface [*Thompson and Solomon*, 2002] as in the GCM.

4. Future Climate

[10] Stratospheric ozone recovery is expected over the coming decades, but at a much slower rate than its depletion [*Austin et al.*, 2003] due to the long residence time of ozone-depleting substances. While the precise rate of future greenhouse gas emissions is unpredictable, most scenarios show quite similar increases through 2050. Thus we expect the influences of these two factors on the SAM index to oppose one another in the future. This is clearly what takes place in the GCM simulations (Figure 2a). As shown in Table 1, the overall high latitude 500 hPa SAM index trend in the GHG+O3 simulation is weakly positive over the next five decades, but not significantly so, as the two forcings roughly balance one another. The projected extratropical trends do retain some SAM-like zonal structure in the mid-troposphere (Figure 4) and above (not shown), due to greenhouse gas forcing. Nevertheless, the simulations indicate that forced SAM index changes will likely play

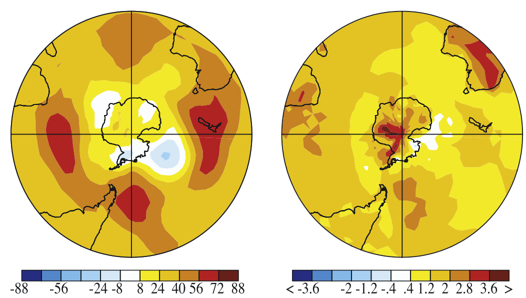

Figure 4. Projected Dec–May change in 500 hPa geopotential height (m, left) and surface air temperature (C, right) averaged over 2000 to 2050 from the simulations forced with projected greenhouse gas and ozone trends.

a much less important role in early 21st century than late 20th century trends.

[11] Recent cooling over the Antarctic continental interior has likely been caused by both ozone depletion and greenhouse gas increases, as both can lead to surface cooling at high latitudes. While those trends closely follow the SAM index, they are more weakly correlated elsewhere in the SH. Regressing the 1970–1999 SLP trend from the GHG+O3 simulations onto the model's SAM pattern (the leading empirical orthogonal function of extratropical SLP, accounting for 39% of the variance), we find that a SAM index shift accounts for 52% of the overall trend. In contrast, only 14% of the extratropics-wide surface air temperature trend projects onto the SAM due to the poor correlation at lower latitudes.

[12] In the future, this decoupling of surface temperature trends from the SAM becomes even more widespread. While climate change in the extratropical SH continues exhibiting annular trends at higher altitudes (Figure 4), and even in SLP to a lesser extent, modeled surface temperature trends over the next five decades bear little resemblance to those associated with the annular mode (Figure 4). Instead, they show the generalized warming maximizing over land areas typical of the response to greenhouse gas increases. Similar decoupling has also been reported in another GCM in response to increasing greenhouse gases [*Stone et al.*, 2001]. Projected surface temperature trends in the model are thus largely determined by changes in the Earth's radiation balance rather than altered circulation patterns, as the latter are quite small. Analysis of instrumental and proxy-data suggest that such a transition out of a SAM dominated regime, perhaps to a global warming dominated one, has already occurred over midlatitudes in New Zealand [*Jones and Widmann*, 2003]. These simulations suggest a similar change for Antarctica, so that the cooling there may reverse due to the effects of a much weakened SAM forcing as the ozone layer recovers and the resulting emergence of the mean greenhouse gas warming pattern. While the model's responses to GHGs and O3 are qualitatively similar to previous studies, it remains to be seen if other models show a similar relative response to these two factors and hence a similar offsetting effect in the future. Results from the upcoming IPCC intercomparison of climate models including all forcings may be useful in this regard.

[13] **Acknowledgment.** Support from NASA's Atmospheric Chemistry Modeling and Analysis Program, programming by G. Faluvegi, and data from D. Thompson and J. Hansen are appreciated.

References

Austin, J., et al. (2003), Uncertainties and assessments of chemistry-climate models of the stratosphere, *Atmos. Chem. Phys.*, *3*, 1–27.

Cai, W. J., P. H. Whetton, and D. J. Karoly (2003), The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO_2, *J. Clim.*, *16*, 1525–1538.

Fyfe, J. C., G. J. Boer, and G. M. Flato (1999), The Arctic and Antarctic Oscillations and their protected changes under global warming, *Geophys. Res. Lett.*, *26*, 1601–1604.

Gillett, N. P., and D. W. J. Thompson (2003), Simulation of recent Southern Hemisphere climate change, *Science*, *302*, 273–275.

Gong, D., and S. Wang (1999), Definition of Antarctic oscillation index, *Geophys. Res. Lett.*, *26*, 459–462.

Hansen, J., R. Ruedy, M. Sato et al. (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963.

Hansen, J., et al. (2002), Climate forcings in Goddard Institute for Space Studies SI2000 simulations, *J. Geophys. Res.*, *107*(D18), 4347, doi:10.1029/2001JD001143.

Hurrell, J. W., and H. van Loon (1994), A modulation of the atmospheric annual cycle in the Southern Hemisphere, *Tellus, Ser. A*, *46*, 325–338.

Jones, J. M., and M. Widmann (2003), Instrument- and tree-ring-based estimates of the Antarctic Oscillation, *J. Clim.*, *16*, 3511–3524.

Karoly, D. J., P. Hope, and P. D. Jones (1996), Decadal variations of the Southern Hemisphere circulation, *Int. J. Clim.*, *16*, 723–738.

Kindem, I. T., and B. Christiansen (2001), Tropospheric response to stratospheric ozone loss, *Geophys. Res. Lett.*, *28*, 1547–1551.

Kushner, P. J., I. M. Held, and T. L. Delworth (2001), Southern Hemisphere atmospheric circulation response to global warming, *J. Clim.*, *14*, 2238–2249.

Marshall, G. J. (2002), Analysis of recent circulation and thermal advection changes on the northern Antarctic Peninsula, *Int. J. Clim.*, *22*, 1557–1567.

Marshall, G. J. (2003), Trends in the Southern Annular Mode from observations and reanalysis, *J. Clim.*, *16*, 4134–4143.

Rauthe, M., A. Hense, and H. Paeth (2004), A model intercomparison study of climate change signals in extratropical circulation, *Int. J. Clim.*, *24*, 643–662.

Rayner, N. A., D. E. Parker, E. B. Horton et al. (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature sine the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Schneider, D. P., and E. J. Steig (2002), Spatial and temporal variability of Antarctic ice sheet microwave brightness temperatures, *Geophys. Res. Lett.*, *29*(20), 1964, doi:10.1029/2002GL015490.

Sexton, D. M. H. (2001), The effect of stratospheric ozone depletion on the phase of the Antarctic Oscillation, *Geophys. Res. Lett.*, *28*, 3697–3700.

Shindell, D. T., D. Rind, and P. Lonergan (1998), Increased polar stratospheric ozone losses and delayed eventual recovery due to increasing greenhouse gas concentrations, *Nature*, *392*, 589–592.

Shindell, D. T., G. Faluvegi, and N. Bell (2003), Preindustrial-to-present-day radiative forcing by tropospheric ozone from improved simulations with the GISS chemistry-climate GCM, *Atmos. Chem. Phys.*, *3*, 1675–1702.

Stone, D. A., A. J. Weaver, and R. Stouffer (2001), Projection of climate change onto modes of atmospheric variability, *J. Clim.*, *14*, 3551–3565.

Thompson, D. W. J., and S. Solomon (2002), Interpretation of recent Southern Hemisphere climate change, *Science*, *296*, 895–899.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl (2000), Annular modes in the extratropical circulation, II, Trends, *J. Clim.*, *13*, 1018–1036.

Waugh, D. W., W. J. Randel, S. Pawson et al. (1999), Persistence of the lower stratospheric polar vortices, *J. Geophys. Res.*, *104*, 27,191–27,201.

Zhou, S., M. E. Gelman, A. J. Miller, and J. P. McCormack (2000), An inter-hemisphere comparison of the persistent stratospheric polar vortex, *Geophys. Res. Lett.*, *27*, 1123–1126.

G. A. Schmidt and D. T. Shindell, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA. (dshindell@giss.nasa.gov)